EPJ Web of Conferences **66**, 03010 (2014)
DOI: 10.1051/epjconf/20146603010
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Search for rotational state of Hoyle state in complete kinematic experiment ^{12}C (α, α′) 3α

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Abstract. An excited state of ^{12}C having excitation energy (E_x) 9.65 ± 0.02 MeV and width (FWHM) 607 ± 55 keV, which decays to three α particles via Hoyle state (E_x = 7.65 MeV), has been directly identified in the exclusive inelastic scattering of 60 MeV ^{4}He on ^{12}C, measured in coincidence with the recoiling ^{12}C Hoyle state (decaying mostly as $^{12}C^* \rightarrow {}^{8}Be_{gs} + \alpha \rightarrow \alpha + \alpha + \alpha$) by event-by-event kinematic reconstruction of the completely detected (4α) events. This state is likely to be a candidate for 2_2^+ first excited of Hoyle state.

1 Introduction

The Hoyle state of ^{12}C, at the excitation energy (E_x) of 7.65 MeV, has been predicted by Hoyle in 1952 based on the ^{12}C abundance in the universe [1] but its precise properties is still not known properly. It was first suggested by Morinaga [2] that the structure of this state has linear chain like deformed structure and it possesses rotational state built on this Hoyle state, i. e., 0_2^+ at 7.654 MeV should also have higher excited states; the lowest excited state has been predicted to be a 2^+ state at excitation energy E_x ~ 10 MeV. However, in spite of vigorous experimental efforts in the recent years, there is still no conclusive evidence so far for these states. In inelastic proton scattering ^{12}C(p, p′) experiments, small angle angular distribution measurement near the diffractive minimum of the broad 0^+ background has indicated the presence of a possible 2^+ state at 9.6(1) MeV of width ~600(100) keV [3, 4]. Recent inelastic α-scattering angular distribution studies also indicated the presence of a 2^+ state at 9.84 ± 0.06 MeV of width 1.01 ± 0.15 MeV [5]. On the other hand, the study of $^{12}C^*$, produced in the β-decay of ^{12}N and ^{12}B, decaying into 3α continuum has however, not found clear evidence about the existence and nature of the 2^+ states at excitations ~10-12MeV [6] and also no evidence found in recent measurement of ^{3}He induced reactions on $^{10,11}B$ target [7]. In contrast, more recently, the γ induced ^{12}C dissociation ^{12}C(γ, 3α) studies have also indicated the presence of a 2^+ state around 10 MeV [8].

It is thus clear that even though there are definite indications about the existence of the elusive 2_2^+ state, the first excited state of the Hoyle state, clear identification of the state is still missing. Assuming the 3α cluster configuration of ^{12}C, the isoscalar (IS) transition rates to various excited states have been calculated by Khoa et al. [9], who have shown that the excited states of the Hoyle

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Article available at http://www.epj-conferences.org or http://dx.doi.org/10.1051/epjconf/20146603010

state band (0_2^+, 2_2^+ , 4_2^+ , ...) should predominantly decay by E_2 transitions to the ground state 0_2^+ , the Hoyle state, which will then decay predominantly via two-step process: $^{12}C^* \rightarrow {}^8Be + \alpha \rightarrow \alpha + \alpha + \alpha$ decay. So, complete kinematical measurement of all outgoing particles in each event may be helpful in reconstructing the events originating from the decay of the excited states of the Hoyle state using missing energy (due to the emission of γ-ray) criterion. However, a recent experiment performed in this line [10], where complete kinematical measurement of all outgoing particles emitted from the reactions $^{10}B(^3He, p\alpha\alpha\alpha)$ at 4.9 MeV and $^{11}B(^3He, d\alpha\alpha\alpha)$ at 8.5 MeV have been done, did not bring out any signature of the possible existence of the 2_2^+ state. Since the spin and isospin zero α-particle is a very good projectile for the excitation of the nuclear IS states [9], we studied the decay of $^{12}C^*$ into 3-body final states (3α) using inelastic α scattering from ^{12}C target to study the excited states of ^{12}C which are predominantly excitable through isoscalar transitions in general, and to look for a cleaner signature of the elusive 2_2^+ state in particular. The present study clearly demonstrates the presence of an excited state of ^{12}C at excitation energy of 9.65 ± 0.02 MeV energy and width (FWHM) 607 ± 55 keV, which is decaying via the 0_2^+ Hoyle state, most likely the excited state of Hoyle state.

2 Experimental Details

The experiment was performed at the Variable Energy Cyclotron Centre, Kolkata, using 60 MeV α beams from the K130 cyclotron on ^{12}C target (self-supported, thickness ~90 μg/cm^2). The Hoyle state (and other excited states) in ^{12}C nuclei were produced through inelastic scattering of α from ^{12}C. The α-particles emitted in the decay of Hoyle state as well as the inelastically scattered α have been detected in coincidence using two 3-element telescopes. The telescopes consisted of a 50μm (ΔE) single-sided silicon strip detector (16 strips, each of dimension 50mm ×3mm), 500μm (E/ ΔE) double sided silicon strip detector (16 strips (each 50mm ×3mm) per side in mutually orthogonal directions) and backed by four CsI(Tl) crystals (thickness 6 cm). The two telescopes were placed at kinematically

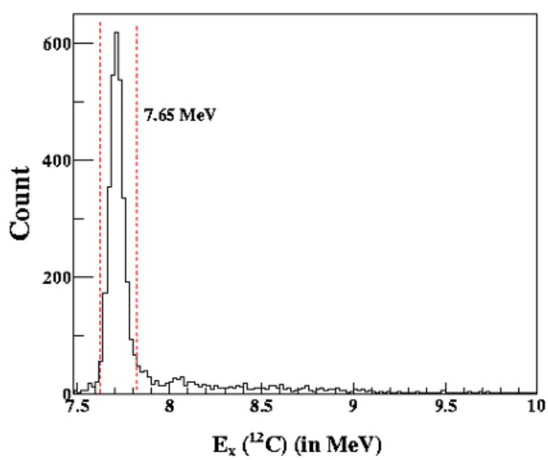

Figure 1. The excitation energy of recoiling ^{12}C reconstructed from the three α-particles emitted in the $^{12}C \rightarrow 3\alpha$ decay. The red lines indicate the gate used for further analysis (see text).

correlated angles for coincident detection of inelastically scattered α in the backward angle telescope (covering the angular range of 104^0 - 128^0) and the three α-particles, originating from the decay of the Hoyle state of the recoiling $^{12}C^*$, at the forward angle telescope (covering the angular range of 14.3^0 - 37.7^0). One horizontal collimator (6 mm width) was placed in front of the backward telescope such that data taking was restricted to only a few (~2) strips around the median plane. So, the corresponding coincident recoiling $^{12}C^*$ nucleus in the forward telescope was also restricted around the median plane; this helped to enhance the percentage of completely detected events (three decaying α-particles confined within the span of the forward telescope and detected) among the whole set of coincident events. Typical beam current used for the experiment was ~5-10 nA.

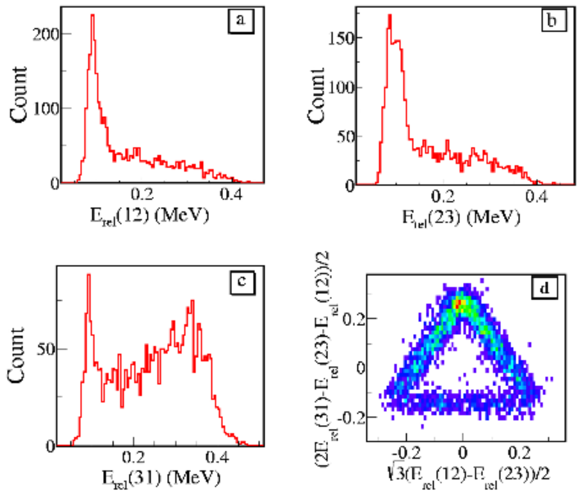

Figure 2 (a,b,c,d). Relative energy spectra for the three decay α-particles, **(a)** between 1 and 2, **(b)** between 2 and 3, **(c)** between 3 and 1, and, in **(d)** the Dalitz plot, for the decay of the Hoyle state (see text).

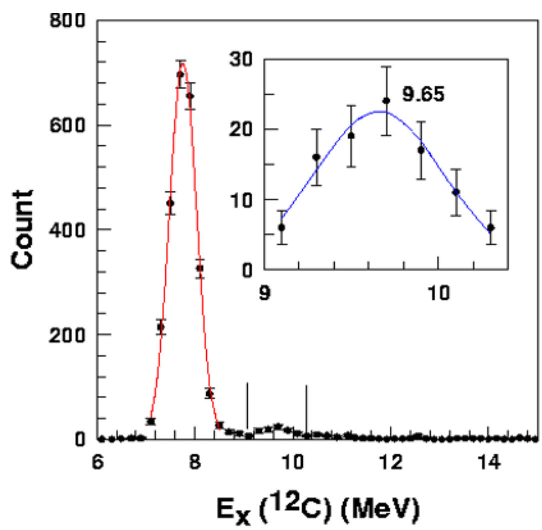

Figure 3. Excitation energy spectrum of ^{12}C from inelastic α-scattering data gated in Hoyle state. The zone marked by the lines has been shown in the inset. The symbols represent the data and the lines are the corresponding fits to the data (see text).

3 Results and conclusion

The analysis of the data has been carried out in steps. In the first step, the energies and momenta of the three α-particles detected in the forward telescope (completely detected event) have been used to reconstruct the excitation energy of the recoiling $^{12}C^*$, which has been displayed in Figure 1. It is seen that the excitation energy has only one prominent peak at E_x (^{12}C) ~ 7.65 MeV, which corresponds to the Hoyle state. In the second step, the nature of decay of the selected events have been investigated further to check if it follows the known decay characteristics of the Hoyle state (predominantly sequential in nature: $^{12}C^* \rightarrow {}^8Be + \alpha \rightarrow \alpha + \alpha + \alpha$). The study has been carried out using Dalitz plot technique [11], utilising the relative energy spectra of the decay particles. The relative energy spectra and the corresponding Dalitz plots for the Hoyle state have been shown in Figure 2. Here, the relative energy indices 1, 2 and 3 refer to the particles emitted with highest, second highest and lowest energies, respectively. All relative energy spectra (Figures. 2a-c) are found to be peaking sharply around ~92 keV, corresponding to the relative energy of the ^{8}Be(g.s.) $\rightarrow 2\alpha$ breakup. The Dalitz plot (Figure 2d) has been generated using the Dalitz parameters $\sqrt{3}(E_{rel}(12)-E_{rel}(23))/2$ and $(2E_{rel}(31) - E_{rel}(12)- E_{rel}(23))/2$, where $E_{rel}(ij)$ is the relative energy between i^{th} and j^{th} particle. The triangular locus in Figure 2d indicates that the decay is mostly sequential in nature (sequential: $^{12}C^* \rightarrow {}^8Be(g.s) + \alpha \rightarrow \alpha + \alpha + \alpha$), in agreement with the earlier findings [12] as well as the recent one [13]. In the next step, the $^{12}C^*$ excitation energy spectrum has been generated from the inelastic α-scattering data of the backward telescope in coincidence with a gate on the observed Hoyle state in Figure 1, which has been shown in Figure 3. It is clearly seen in Figure 3 that the $^{12}C^*$ excitation energy spectrum obtained from the inelastic α-scattering contains two peaks. The first peak, at 7.73 ± 0.09 MeV is the 0_2^+ Hoyle state. In addition, there is a small peak also seen at excitation energy ~ 9.65 ± 0.02 MeV (see inset of Figure 3) . The width of the Hoyle state, which is actually negligible (see Figure 1), appears to be quite broad in the inelastic scattering spectrum (Figure 3). This is due to the fact that the inelastic scattering spectrum has been generated by summing over a large solid angle to extract statistically significant information about the excited state; the observed broadening is therefore of kinematic origin associated with the total angular coverage and the angular resolution of each strip. The excited state observed at 9.65 ± 0.02 MeV is having a large intrinsic width, which is estimated to be ~607 ± 55 keV, obtained after correcting for the kinematic broadening. Since this state has been seen in coincidence with the Hoyle state, it is likely to be an excited state of ^{12}C, which is decaying via Hoyle state.

It may therefore be concluded that the ~9.65 ± 0.02 MeV excited state of ^{12}C seen in the inelastic α-scattering spectrum in coincidence with the Hoyle state reconstructed from kinematically complete events, is most likely a new excited state decaying via Hoyle state. In absence of detailed angular distribution measurement, it is not possible to assign the spin, parity of this state. The energy and width of this new state are quite close to the those predicted for the first excited 2_2^+ state of the Hoyle state band from the inelastic scattering angular distribution studies [3-5] as well as using gamma-ray beam scattering from ^{12}C [8]. Since the state has been directly observed for the first time decaying directly via Hoyle state, this new state may be a candidate for the 2_2^+ state of ^{12}C. Further analysis with detector efficiency correction is going on for detail calculation of its branching ratio of particle to gamma decay. Detailed angular distribution of this state should be carried out for proper identification of this state.

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